ELECTROMAGNETIC CONSTRUCTION OF A 1 KM-RADIUS RADIATION SHIELD

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Abstract

A fundamental obstacle to building human settlements in orbit is the construction of the massive outer radiation shield. This problem is used to illustrate the relevance of a comprehensive plan in developing a Space-based economy (SBE). The problem of building the shield of a one-km-radius, two-km long cylinder is revisited in the light of recent studies on bootstrapped lunar solar-electric power plants, mass drivers, and autonomous spacecraft. Architecture for the project is discussed. This test case violates the usual assumptions about Space exploration in that it deals with constructing a massive, spacious structure with relatively simple technology to demonstrate a viable path to the infrastructure of an SBE. The example shows that both the technical feasibility and the affordability of such a human settlement rise substantially when viewed in the context of a comprehensive program for a SBE.

Introduction

Since the 1970s, there have been several studies on the steps needed to create a flourishing society beyond Earth[1]. Gerard O'Neill[2] detailed the logic and motivation for the creation of such a society, and laid out examples to visualize several of the initial steps. Thus, the following concepts are not new: (a) the benefits of extracting materials from above the Earth's gravitational well, (b) electromagnetic launchers on the Moon, (c) Shuttle Main Fuel Tanks joined into storage stations, (d) oxygen and metal extraction on the Moon, (e) solar-heated glass manufacturing, (f) self-propagating machines to bootstrap lunar manufacturing and mass-drivers, (g) teleoperation of lunar and orbital facilities, (h) orbital assembly of lunar-derived solar power stations and spacecraft for long-duration missions, and (i) large orbiting cities largely self-sufficient in food and other basic resources. From kindergarten to the SSI, there is general agreement amongst Space enthusiasts about their technological feasibility and the need for focused, fast paced, internationally competitive Space programs, which will generate huge benefits to humanity.

Yet, in May 2001, the human presence beyond Earth is limited to a very few government employees and robots who are sent up, entirely dependent on earth-launched resources. The only permanent facility beyond Earth is the ISS, whose total living space of 100 cu. m is comparable to that of a kindergarten classroom. While commercial spending on Space, worldwide, surpassed government spending as of 1997[3], and the satellite business generated over \$81B in revenue[4] in 2000, the Space industry and the exploration/ utilization programs cannot be described as being "healthy". The "Gold Rush into Low Earth Orbit" [5] seen in 1999, has stalled with the demise of the Iridium satellite constellation system, and the difficulties faced by most launch system startups. NASA's X-30, X-33 and X-34 programs stand canceled. The Mars program has seen a dramatic drop in ambition level from "Permanent bases by 2018" in 1985, to "robotic exploration missions to Mars Orbit until 2020" in 2001[6]. Cost "growths"[7] on the ISS have forced NASA to cut into even these modest plans in 2001. It is appropriate to ask: *"What can be done differently to change the rate of progress?"* This paper sets out the idea of a Space-Based Economy, then discusses the construction of a large space-based structure to illustrate changes in technology and the effects of a comprehensive plan.

Space Based Economy

It is non-controversial today to postulate that a Space-Based Economy is the correct motivator for a strong Space program. The obvious promises of unlimited extra-terrestrial resources and a low gravity production environment buttress the argument. Yet the term "Space-Based Economy" requires some explanation. Today there are two competing perspectives on Space Commercialization.:

(a) a colonial economy, where the space entrepreneur aims to manufacture goods and materials that can be sold on Earth. They can either be high quality, high cost goods, such as crystals and drugs, or low cost, high volume products, such as television signals, and

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(b) a prospector economy, where the entrepreneur tries to mine rare metals and other precious materials that command "astronomical" prices on Earth.

Though apparently at odds, these approaches converge on several key items:
1. Earth as the only possible market.
2. "Faster-better-cheaper" to compete in today's global business environment.
3. Three-to-five year Return on Investment (ROI)
4. Terrestrial launch cost reduction as key enabler.
5. Both approaches are in heavy weather today.

Nathan Goldman[8] divided Space Commerce into four sectors: transportation, communication, remote sensing and manufacturing. In 1992, he added infrastructure to this list[9]. He viewed transportation as the key to Space Commercialization. McLucas[10] offered a more view of space commercialization, restricted to Earth-orbiting satellites. The KPMG Peat Marwick[11] survey also pointed out that space investments are just like other investments and space entrepreneurs need to concentrate on business plans.

Public support for the Space program is either flat or declining in the US. Recent surveys[12] found (a) that people wanted to see NASA completing programs, and (b) that lawmaker support for the Space program came primarily from constituencies which include large NASA centers or other aerospace facilities which benefit from the NASA Space budget. This leads to the issues presented in this paper. Our central postulate is that the best argument for a Space program is the development of a Space-Based Economy (SBE). *A true Space-Based Economy is one where most raw materials and products originate and are consumed outside Earth*. Such an economy must be able to grow steadily with minimal Earth-based support. This implies: (a) large Space-based infrastructure, (b) extra-terrestrial raw materials extraction and processing capabilities, (c) large scale manufacturing capabilities in space, and (d) exchange of products and services between space-based enterprises. The "critical mass" of such an economy is large, and *includes a vast diversity of businesses and professions, thereby directly involving a broad cross-section of the tax-paying public*. At once, it makes a large percentage of the US population stakeholders in the Space program. The concept of a Space Based Economy also addresses the three problems cited for the lack of success of the Space Exploration Initiative which was outlined by President George Bush I on July 20, 1989.[13]

1. *Purpose:* SBE provides a tangible and realistic purpose to space exploration. Reasonable estimates of the increase in GDP and taxes have been done in the past.[9]
2. *Vision:* SBE provides a grand vision that unifies discrete concepts. Proponents of robotic exploration, human exploration, Lunar resource utilization, Asteroid resource utilization can all fit into the vision of a Space Based Economy.
3. *Infrastructure:* SBE encourages Government-Industry cooperation. The development of a space based economy follows the 'policy resilient approach', which builds up the infrastructure to support multiple uses and goals. Realistic short-term projects can be integrated into the fabric of a Space based Economy.

With the above requirements in mind, we can come up with the following postulates:

1. With the long-term aim of developing a civilization in space, the first step is to establish a space-based marketplace.
2. Large scale manufacturing in space is possible, often with minimal human presence and intervention.
3. A synergistic approach is required between space-based businesses to ensure mutual success of Business Plans.

An excellent start to this synergistic process can be found in the Proceedings of the Space 2000 Conference of ASCE [14], which brought experts from diverse fields such as law, biology, mining, architecture, rail transportation, K-12 educators together with space scientists and rocket engineers.

The critical difference in approach that we propose is the development and articulation of a comprehensive plan for an SBE. The potential role of the technical community of Space enthusiasts such as the SSI in such an endeavor is large: (a) to define the needs for various technologies and services, (b) to develop accurate knowledge banks on the special aspects of Space, and the steps needed to complete given projects, (c) to identify the linkage between costs and lead times for various pieces of the SBE and (d) to educate the public about the potential and the realistic opportunities, given their willingness to support a large and concerted effort. The difficulties in generating a credible case for the SBE are:

1. How to describe such an economy, with sufficient technical and economic credibility, in steady-state growth mode, with minimal dependence on Earth, yet generating income for investors/taxpayers on Earth. This would be analogous to trying to describe the present city of Atlanta, in a report written in the year 1600, and is bound to be different from what eventually occurs. However, sufficient documentation exists to construct reasonable predictions, which will get entrepreneurial minds thinking once some examples are shown.

2. How to show, before generating the entire interlinked SBE model, that such an economy would experience efficiencies of scale and mutual interest, which will provide viable solutions to the problems which are today seen as insurmountable by current approaches.

We attempt to start dealing with the second problem here. The hope is that the issues discussed will trigger thinking towards the solution of both problems.

Building a 1km-radius Radiation Shield Using Electromagnetic Construction

To illustrate how such a plan can bring about revolutionary change, we start by reconsidering the problem of building the radiation shield of a cylindrical "settlement", 1km in radius, and 2 km long, built at the L-2 Lagrangian Point of the Earth-Moon system[2]. This test case violates the "usual" assumptions about Space exploration: it deals with constructing a massive, spacious structure with relatively "low-tech" methods, and mostly "Moon dirt", to demonstrate a viable path to the infrastructure of a Space-based economy.

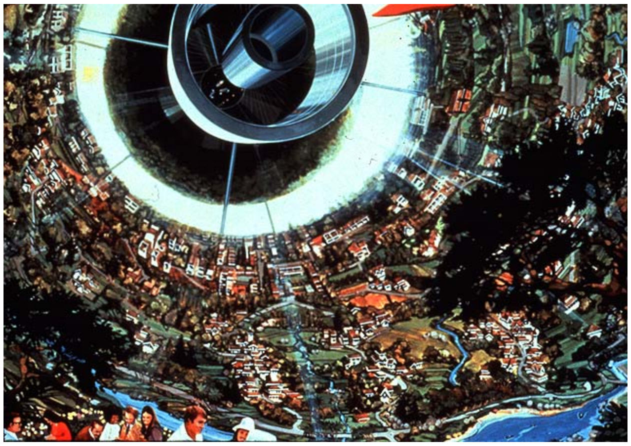

Figure 1: Island One, a Space settlement in orbit, with people living along the equator of a rotating sphere [1,2,15].

Several visionaries have studied the dream of "Outposts" in space: great space cities which will act as stepping-stones for humanity to venture out into the Solar System and beyond. Figure 1 shows "Island One", a 1-km-radius orbiting community at the Earth-Moon L-5 Lagrangian Point, described by O'Neill[2]. The "Bernal Sphere" would spin co-axially with toroidal agriculture modules, with artificial gravity close to one Earth 'g' near its equator. A 1976 expert study of technologies[16] settled for a toroid to provide the highest artificial gravity at the lowest rotation rate, mass and cost for a small station. The toroid could also be used to generate magnetic fields to deflect charged particles. This was later rejected as impractical, so that the shielding problem remained. The shell of the Bernal sphere, made of aluminum ribs, sheeting and glass (to admit sunlight), supported by radial cables, constituted a tiny fraction of the mass compared to the radiation shield. Two fundamental obstacles to building such communities are: (a) the need for human or human-like robotic labor, and (b) transportation and cost of the immense mass of the radiation shield. A shield made of sand or soil would be 2 meters thick[16]. The material was assumed launched by a nuclear- or gas-powered lunar electromagnetic mass driver. Human labor had to be sustained from Earth and protected until the shield was complete, the sphere pressurized and sealed. Even at projected STS launch costs of \$110/lb to LEO[2], versus today's \$12000/lb, this was prohibitively expensive and dangerous. New ideas are essential to automatically form the radiation shield.

We choose a cylinder for illustrative purposes because (a) the geometry is simple, (b) it is scalable by simply extending the length, (c) it provides uniform "g" along the circumference and (d) it suits our construction scheme. For the case in question, the 2m thick shield has a mass of 5-x10^{10} kg. Whether the ends should be capped, and with what material, are details not addressed here: capping the ends would add more mass and time, but not change the basic parameters of the discussion.

Ideally, material from the Moon or asteroids would move into position and attach to the outer frame of the "city" under automatic control, using solar power. Earth-based humans control construction at the Earth-Moon L-2 or L-5 using near-real-time video feedback if needed. The radiation shield forms over a decade. With some interior structure also built robotically, human habitation waits until the Settlement is safe and hospitable. The immense scale of the construction forces, repetitive effort and machinery is the problem.

Below, we present a simple discussion of how such a huge structure may be built using automation and telepresence from Earth, with lunar-derived materials, and solar energy. The bootstrapping sequence is considered briefly. The real intent is to see the effect of undertaking such a project as a part of a coherent SBE, as opposed to a stand-alone project. There are seven important differences between the models of 1975 and today, shown in Table 1.

Table 1: Important Differences Between 1975 and Present Models for Space-City Construction

#	1975 models	Present model using Tailored Force Fields (TFF)
1	$110/ lb Earth-LEO	$1,300 to $14,000 per lb to LEO
2	Human labor for all construction and operation.	Robotic. Earth-based human intervention to verify, trouble-shoot & redirect. Robotic craft (NEAR) prove feasibility
3	Construction at L-5	Shell construction at L-2 followed by slow move to L-5
4	Lunar mass driver gas-powered; H2 from Earth.	Lunar-equatorial Solar-power fields . 20 launchers around the lunar equator enable round-the clock launches; no fuel cost.
5	Baseball-size loads. High Isp. Debris threat. 30g; 10km run	Railcar-sized payloads. 8-g accel'n: lower structure weight, longer track. Minimize alignment problem. Simpler load capture.
6	Entire interior pressurized for "shirt-sleeves" comfort.	Only 10 to 30 meters at rim pressurized, using membrane with 30-meter bubbles to provide micro-climates as needed.
7	Machinery required to make panels etc.	Non-contact Acoustic Shaping with solar-heated powder sintering & furnaces. Robotic assembly of payloads.

Other aspects:

- The 1km radius permits 1-g with 0.95 rpm: this is within the comfort parameters of the vast majority of humanity[2]. It thus removes one of the prime obstacles to the popular appeal of the space program: the idea that one has to be a super-fit youngster trained to military levels to participate in Space.
- The net output rate of the lunar mass drivers controls the time needed to build the city shell.
- The basic unit used in building the outer shell is a rectangular container similar to an open-top railroad boxcar: the 2-meter depth of regolith provides adequate radiation shielding[16]. The car bottom and sides are manufactured on the Moon from metal extracted there; industrial-type robots assemble the cars, load them with lunar regolith and place them on the carriage of a launcher. Following acceleration at 8g to 2.4km/s, (40km of track) each car is launched into lunar orbit with sufficient energy to reach L-2. Note: The alternative technology of Space Tethers and "Space Elevators"[17] could be used for the launch instead of mass drivers. The large cars and very long track specified here are not optimal for mass drivers[18]; however, we use a conversion efficiency of 50% from electricity to launcher work, compared to the 92% claimed for high-frequency, 100-g launchers of 20kg payloads[18]. With automated lunar metal extraction and launcher construction, it is argued that a launcher based on large payloads and low acceleration (8g) will offer far greater versatility to cater to a variety of commercial uses including the transport of humans, and would therefore be a better infrastructure investment.

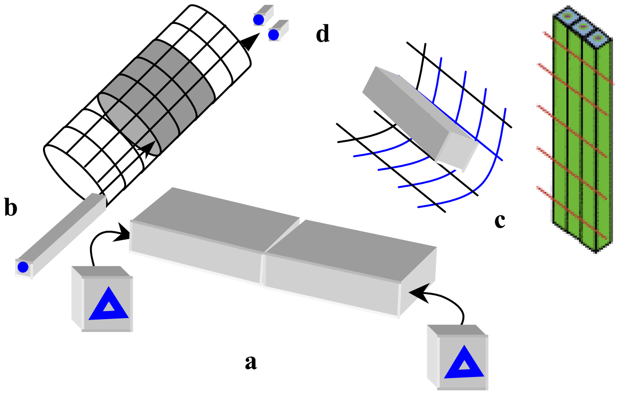

Figure 2: Construction sequence of the cylinder. (a) Shepherd units connect two loads into a load-train. (b) Train arrives at wire Grid (c) loads are delivered into place, (d) Shepherds leave to pick up another pair of loads. (e): loads fastened to cable Grid and each other, forming support structure.

- Two orbiting "shepherd" propulsion units will each use gas thrusters (solar-heated H_2 or He) to rendezvous with a load, then join the loads back-to-back and guide this "train" to the entrance to the 1km-dia cylinder. Helium for the orbit-transfer may be from the Moon; else Earth-shipped H_2 will be used.
- Structural strength comes from a Grid of cables made on the Moon and launched initially from the Moon for deployment in orbit. Rings of 12.5mm dia. cable segments, 1km in radius, spaced 4 meters apart, will be connected by longitudinal cables 45 degrees apart. The Grid is powered by solar panels, with hydrogen or helium thrusters to provide orbit corrections. Every node of the Grid will be an electrical switching unit, so that a strong electric current can be passed through any segment of the Grid independently. Rotation about the axis, initiated using small thrusters, holds the grid in tension during shell construction.
- A radial arm moved along and around the axis holds an inner current-carrying Grid segment.
- Each "train" enters the grid along a longitudinal trajectory with respect to the Grid at a relative speed of 1km/h. This can be achieved using the orbit of the Grid about L-2, and the mass-driver launcher. A refinement would be to incorporate a floating cable on a winch at the axial hub of the cylinder. As the construction proceeds, the Grid spins up slowly due to thrusters placed on the outside. Loads would arrive near the cylinder axis, catch a free cable, and drift outward as the cable imparts tangential momentum, reaching a relative velocity of 1km/h with respect to the outside of the grid when it arrives.

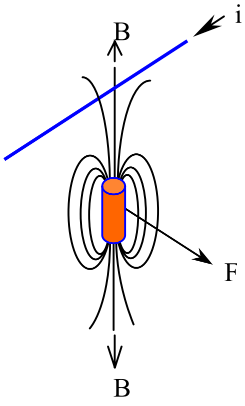

Figure 3: Electromagnets on the Shepherds activate to induce forces in the field between energized cable segments.

A trio of fuel cell powered electromagnets on each Shepherd is activated to decelerate and attach the boxcars to the grid. Lunar LOX and Earth-shipped H_2 power the fuel cells. The Shepherds are then released and accelerated by the inner grid for their journey back to catch new box cars and form the next train: a thruster burn may be needed. Radial force due to rotation keeps the boxcars in position and fasteners activate to fix them to the Grid.

- The boxcar floors are the outer skin. Regolith 2m thick is the radiation shield.
- Boxcar sides will be joined together (a repetitive operation with several options) to form ribs with 2m depth in order to withstand the centrifugal stresses. The initial rotation rate is kept just adequate to keep the cable grid in tension, and is limited by the cable strength, being increased to the final 1rpm value steadily as the ribs are formed.
- With adaptive control as construction proceeds, the ΔV for orbit-transfer and positioning can be continuously minimized; just how close to zero remains to be seen.

By controlling current amplitudes, directions and segments, as well as the force interaction due to the electromagnets on the Shepherds, mass is maneuvered accurately and safely into desired positions, piece by piece. The wire Grid (Fig.2) works with DC or very low-frequency current changes. With two independent wire grids (inner and outer), and individually controlled electromagnets on each Shepherd unit (see Fig. 3), arbitrary force directions can be obtained.

Table 2: Architecture of 1km cylinder radiation shield:

- Radius = 1km
- Length = 2km
- Shield Depth 2m
- Rotates at 0.945 rpm for 1g
- Grid current = 35 amps
- 500 loops of cable; Wire dia =12.5mm
- Solar Panel area to power grid = 350 m^2
- Boxcar dimensions: 2mx2mx 20m
- Mass/ load: 160,000 kg. Regolith sp.gr.=2)
- 10 launchers operational at any time (20 total around lunar equator)
- Shepherd unit current required: 5 amps
- Time to build: 10 yrs.

Construction parameters are listed in Table 2. These look 'feasible'; i.e., do not require yet-to-be-discovered substances or physical phenomena. As was known before, the cost of building the City is dominated by that of the radiation shield and outer shell. With our proposed automatic technique, the cost of actually building the shell is made negligible in comparison with that of delivering the huge amount of material to L-2. Again, the operating cost for this delivery is negligible (little recurring fuel cost except for orbit corrections of the Shepherds) compared to that of amortizing the electromagnetic launcher. With the congruence of various needs for such launchers on the Moon, the construction of the radiation shield for a 1km-radius, 2km long City becomes quite feasible.

Shepherd Propulsion/guidance units: The loads themselves are kept simple: we need $\pi*10^5$ of them, built quickly and efficiently on the Moon. The launcher "bucket" incorporates the electromagnetics for acceleration, and releases the load at the speed and attitude to reach the right speed at the Grid. The transit time to L-2 can be weeks if needed. The Shepherds have thermal and electromagnetic propulsion. Outside the Grid, they use solar-heated on-board gas (He or H2). Once inside, an H2-O2 fuel cell powers any of 3 electromagnets arranged in a Δ on each Shepherd. The principle of electromagnetic propulsion inside the Grid is shown in Fig. 3. Radar guidance and fuel resupply for the Shepherds can be centralized on the Grid, and transmitters can beam energy for propulsion from the Grid's solar arrays. Thus electro-magnetic construction cuts the construction cost to a tiny fraction of the cost of obtaining the material. The construction can be done inside 10 years, with minimal human labor or risk.

Discussion

It is not possible to talk about a business plan for a space-based business as a discrete entity. The various industries such as mining, lunar launch etc have to become real in a coordinated manner, since their business plans support and buttress each other. They are the cogs that come together to drive the Space based Economy. A realistic business plan cannot be drawn up by one business alone, as it needs inputs from other space based industries.

The concept of a Space based Economy brings these businesses together. The business plan of a single industry that may appear risky and unsubstantiated when viewed by itself, can become realistic when patched into the network of a Space based Economy. For instance, the prevailing Business paradigm may no longer be realistic in the Space based Economy. Present Business thinking looks at pricing strategies from three perspectives.

1. Price to Penetrate: a low-priced strategy to garner market share.
2. Skimming the Cream: a high-priced strategy to make quick profits even at the cost of losing customers.
3. Loss Leader: an ultra-low priced strategy to eliminate competition.

This pricing paradigm is no longer sufficient to cater to the space based economy. The pricing strategy required is what we call 'Mutually Assured Survival' pricing. With a limited number of customers, space business providers have to work synergistically with their customers. For example, the pricing of the lunar launch industry has to be just right so that it covers a sufficient return to its investment, while at the same time guaranteeing survival to its limited customer base.

Cost Estimation Approaches

Obviously, cost estimation for such projects poses huge uncertainties. Several levels of estimation can be considered. The first is the 'Delivered Cost Approach' [19] where we argued that the cost of materials delivered at a given point in Space would be limited (a) from above by the cost of getting similar materials delivered from Earth and (b) from below by the supplier demanding the most that the market will bear. This approach will result in few projects being feasible, but does offer an upper bound to cost. Secondly, one can imagine a situation where one assumes the risk of constructing the entire Space-Based Economy, and looks at this capital cost. This can be done by speculative comparison with historical data such as the development of the State of Alaska, or the growth of the present Space-related economy. A third approach is to bring in all players at the outset, and figure the costs and risks to each, given the presence of the rest.

Prior work on Space Manufacturing looks at manufacturing in space using non-Earth based resources and energy[20]. One approach was to develop a step-by-step bootstrap program that piggybacked upon the space shuttle program[21]. Space manufacturing has also been viewed as a self-regenerative resource and production loop outside the Earth's biosphere, which would serve as a revenue generator to capitalize further the Earth-Moon region, and its integration into the economy of the World.[22] Cheston[20] remarks upon the differences between Space Manufacturing and Space Colonization. He advocates an evolutionary approach to bring Government and private funding together. He ends by saying: "For these factors to emerge simultaneously would require an unusual amount of luck; or the development of an informal alliance of properly placed individuals".

Vajk[23] differentiates a large-scale terrestrial project from a project in space. He points out that for creating a new Space industry, e.g. a SPS, it is necessary to create numerous other industries such as mining, chemical processing, transportation, housing etc. He comments that in the long run, a mature, diversified industrial society would develop in Space. This aspect can be used to achieve symbiosis in the business plans of these industries. The Report of the National Commission on Space, 1986,[24] also emphasizes an economical, phased approach for space exploitation, which will be technically reasonable, and will support private enterprise. It focuses on the benefits that can accrue to humanity and the nation in particular. The report, however, stops short of outlining a clear vision of the concept that will integrate Science, Technology and Economics. That concept is the Space based Economy.

Costing the Radiation Shield Project

The advantages of articulating the Space based Economy can be seen from the reduction of public funding possible due to the establishment of private businesses within the framework. The establishment of private businesses becomes possible due to the assured markets from the other businesses and Government projects. An assessment of the public funds required is based on published estimates for various projects. Ignatiev[25] estimates the cost of a robotic 10,000 MW solar power plant on the Moon as $ 62B in year 2000 dollars. This will have a multi-customer base, including mining, fuel extraction, manufacturing and launch services. The cost for Strip Mining on the Moon is estimated as $ 3 billion in year 1979 dollars[26], extrapolated using Consumer Price Index Inflation to $ 8 billion in year 2000 dollars. This is conservative, considering advances in the processes compared to 1979. Another spin-off business is the Lunar Launcher System. The cost in 1977 dollars[27], adjusted for inflation, gives a Present Value estimate of $8B. The results are seen in Figure 4. If the construction of the radiation shield were undertaken as the culmination of a Space Infrastructure project, it would cost over $110B. If the project could purchase power at the quoted rate[25] of $0.39/KwH, the project cost comes down to $80B, while assuring the power-producers of demand during the initial decades of their production. With lunar power production underway, the mining industry can commence operations, and start producing materials for extracting metals and fabricating components for the launchers, among other items. Again, the radiation shield project provides an assured market, reducing its risk costs, and the cost of the radiation shield project itself. With power generation, resource extraction and component manufacture underway, the cost of building the launcher comes down, and again there is an assured and diversified market to reduce risks in its development. This, for instance, is a prime reason to depart from the previous small-payload / high-accleration optimum for the launcher and go to a large payload / low-acceleration system. The horizontal axis of Figure 4 makes the point that the drive towards one-shot missions and "3-to-5-year ROI" can be replaced by a planned, sensible pace of development, with its benefits clearly visible.

Thus, the vision of a Space Economy can bring the various business enablers together, and enable them to articulate business plans that seem realistic and achievable. It can also drastically reduce Government involvement in infrastructure development in space, while at the same time providing opportunities for enhanced Economic activity and taxes for the Government.

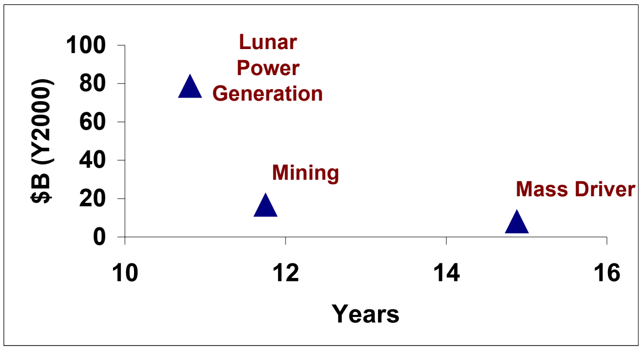

Figure 4: Reduction in public expenditure due to private space based industrial corporations.

Alaska Analogy

The above discussion will certainly generate some head-shaking, as people see that we are still discussing the expenditure of hundreds of billions of tax dollars in moving dirt from a vacuum desert to an empty shell 200,000 miles away from Earth. Let us compare this expenditure level with other projects with which we are reasonably comfortable. We will use one example where the infrastructure was mainly developed in order to bring out valuable resources. A second example will examine how a marketplace grew on the basis of ideas and technology which simply did not exist when the initial investments were made.

In the State of Alaska the wellhead value of the oil produced until 1993[28] is about $265B (in 1993 dollars). The total development costs were $67 billion, leaving $198B to be divided among the producers and federal and state governments. So far, Alaska's royalties and income, production, and property taxes have totaled about $75B. Slightly less than half of the remaining cash flow, about $55 billion, is estimated to have been paid in federal income taxes, lease payments, and the windfall profit tax. The remainder, about $57 billion (less than one-fifth of the gross revenue) has accrued to the individuals and companies that discovered and developed the resource[28]. This example suggests a 300% return on investment from an economy which exists on resource extraction and export. In the case of the SBE, the resource export may not be to Earth, but to places where it brings the most revenue. Examples are liquid oxygen delivered to stations in LEO to refuel cryogenic transfer stages, or to other stations to fuel long-duration Space exploration missions. The money from these resources has gone back into Alaska to a large extent and resulted in the creation of a modern infrastructure and society, a far cry from the time when missions to Alaska had to carry all life support systems as payload, with narrow launch windows, and a very high risk of failure and death.

Though the Alaskan experience is not a perfect analogy, it gives an idea of the wealth that can be generated in both the existing American economy and the new economy developed. With increasing inhabitation of the new economy, it is inevitable that it will reach a critical mass that will convert it into a self-sustaining economy: an economy that exists with minimal external intervention, yet generating considerable resources for investors who may not be a part of it.

The second example is today's Space business itself: as seen before[4], the annual revenue exceeds $116B including both commercial and government expenditures. Much of this is on needs, activities and technologies which would have been considered quite unimaginable 60 years ago, but which developed as new capabilities came on line and got entrepreneurs and technologists thinking. Fundamentally, this economy does not take anything away from Outer Space nor bring in anything except information and knowledge.

Concluding Remarks

This paper has taken a meandering route to examine some of the possibilities of a Space Based Economy of the (hopefully not distant) future. The construction of a massive radiation shield, a project considered hopelessly impractical using approaches of the past, is shown to be quite feasible using well-known technologies, current levels of automation and telepresence capabilities, and a coherent plan for developing a mutually-supportive network of economically-useful projects. The steps in building the radiation shield are illustrated in Figure 5. The costs, lead times and technical demands are seen to be well within the bounds of what is possible today.

References

1. Space Studies Institute. http://www/ssi.org
2. O'Neill, Gerard K., "The High Frontier: Human Colonies in Space". William Morrow & Co, NY 1977
3. Covault [1998a]: Covault, C., "Global Commercial Space Business Sought for ISS". Av. Week & Space Tech, May 11, '98, p. 26
4. Anon, "Commercial Satellites generated $81.1 billion in revenue last year..". Av. Week & Space Tech, April 9, 2001, p. 22
5. Beardsley, "The Way to Go Into Space". Scientific American, February 1999, p. 80-97.
6. NASA HEDS Strategic Plan. www.hq.nasa.gov/osf/heds/hedsplan.html
7. Morring, F., "ISS Cost Growth May Continue". Aviation Week & Space Technology, April 9, 2001, page 39.
8. Goldman, N., "Space Commerce: Free Enterprise on the High Frontier", Ballinger Publishing, Cambridge, MA 1984
9. Barnett, M.B., "Fifteen Years of Commercial Space in retrospect", Proc. Fifth Intnt'l Conf. on Space, Albuquerque, '96.
10. McLucas, J.L., "Space Commerce", Harvard Univ. Press, Cambridge, MA.
11. KPMG Peat Marwick LLP and Space News, "Space Finance Survey, Washington DC., '91.
12. Surveys by university teams from U. Texas and M.I.T., cited in Matos. C.A. et al, "Developing the Space-Based Economy: An Architecture for NASA Mars Customer Engagement". "NMB Program", 2001. www.adl.gatech.edu/nmb/nmbhome.html
13. Marshall, M.F., "The Space Exploration Initiative: Its Failure and Lessons for the Future", Proceedings of the Fifth International Conference on Space, Albuquerque, NM, '96.
14. Space 2000. Proceedings of the Seventh International Conference and Exposition on Engineering, Construction, Operations, and Business in Space American Society of Civil Engineers, Albuquerque, NM, February 2000.
15. NASA Web Page on Space Settlements. http://www.nas.nasa.gov/Services/Education/SpaceSettlement/70sArt/art.html
16. Johnson, R.R., Verplank, W., O'Neill, G. K. et al: "Space Settlements: A Design Study". Report, NASA-ASEE Engg. Systems Design Summer Program, Ames RC, CA, Aug. 75.

http://lifesci3.arc.nasa.gov/SpaceSettlement/75SummerStudy/Table_of_Contents.html

17. Edwards, B.C., "The Space Elevator". NIAC http://www.niac.usra.edu/studies/
18. Chilton, F., Hibbs, B., O'Neill, G., Phillips, J., "Electromagnetic Mass Drivers". In O'Neill, G., Ed., "Space-Based Manufacturing from Nonterrestrial Materials".Prog. in Astronautics and Aeronautics, Vol. 57, AIAA, '77.
19. Ganesh, B., Matos, C.A., Coker, A., Hausaman, J., Komerath, N.M., "A Costing Strategy for Manufacturing in Orbit Using Extraterrestrial Resources". Proceedings of the Second Space Resources Utilization Roundtable, Golden Co, Nov. 2000
20. Cheston, S.T., "Space Industrialization Social Science Interactions", Space Industrialization Vol. 2., CRC Press, FL, 1982.
21. Driggers, G.W., and Newman, J., "Establishment of a Space Manufacturing Facility", Space Based Manufacturing from Non-Terrestrial Materials, Vol.57.
22. Cheston, T.S., "Space Stations and Habitats", Proceedings of the 72nd Annual Meeting of American Society of International Law, Lancaster Press, Lancaster, PA, 1978.
23. Logsdon, J.M., "The Decision to go to the Moon: Project Apollo and the national Interest", U.Chicago Press, Chicago, 1970.
24. "Pioneering the Space Economy", The Report of the National Commission on Space, 1986.
25. Ignatiev, A., "A New Architecture for Space Solar Power Systems: Fabrication of Silicon Solar Cells Using In-Situ Resources". NIAC http://www.niac.usra.edu/studies/
26. Carrier, W.D., "Excavation Costs for Lunar Materials, Fourth Princeton/AIAA Conf. on Space Manufacturing Facilities, May, 1979.
27. Arnold, W.A., et al, "Mass Drivers: Engineering", Space Resources and Space Settlements, 1977, NASA SP-428.
28. Van Vactor, S.A., "Time to End the Alaskan Oil Export Ban". The Cato Institute. Policy Analysis No. 227, May 18, 1995, http://www.cato.org/pubs/pas/pa-227.html

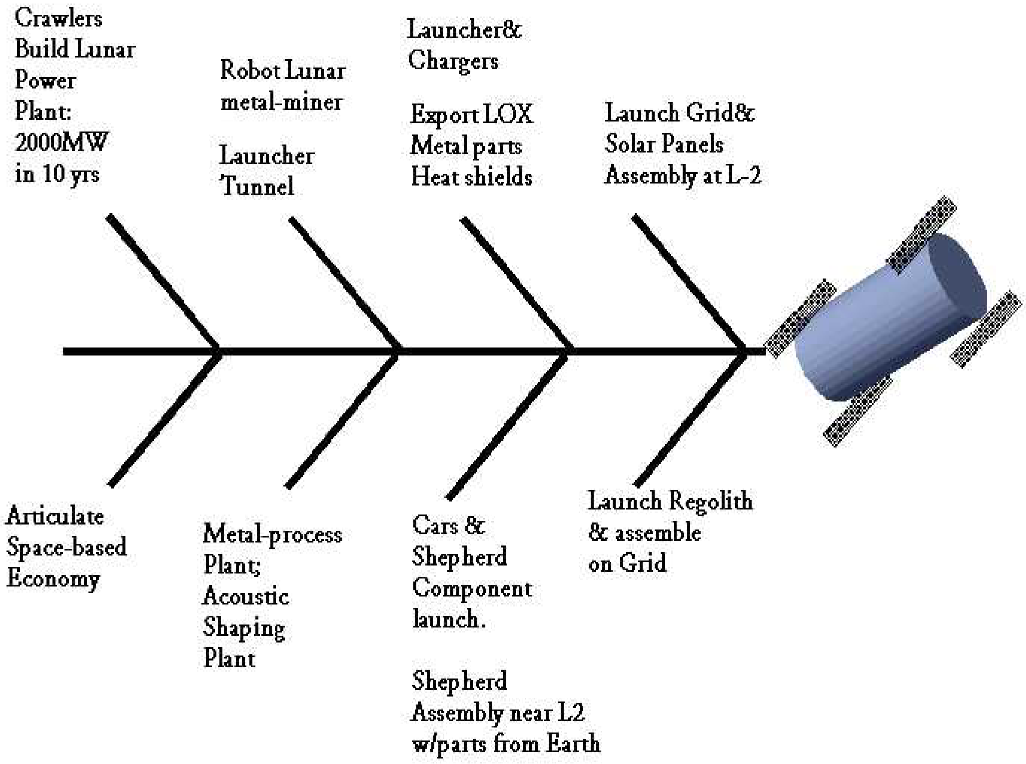

Figure 5. Process to develop the major infrastructure elements of a Space-Based Economy